Exploring Halo Substructure with Giant Stars: The Dynamics and Metallicity of the Dwarf Spheroidal in Boötes

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ABSTRACT

We report the results of a spectroscopic study of the Boötes (Boo) dwarf spheroidal (dSph) galaxy carried out with the WIYN telescope and the Hydra multifiber spectrograph. Radial velocities have been measured for 58 Boo candidate stars selected to have magnitudes and colors consistent with its red and asymptotic giant branches. Within the 13′ half-light radius, seven members of Boo yield a systemic velocity of $V_r = 95.6 \pm 3.4$ km s^{-1} and a velocity dispersion of $\sigma_{\rm o} = 6.6 \pm 2.3$ km s^{-1}. This implies a mass on the order of 1×10^7 M$_\odot$, similar to the inferred masses of other Galactic dSphs. Adopting a total Boo luminosity of $L = 1.8 \times 10^4$ L$_\odot$ to 8.6×10^4 L$_\odot$ implies $M/L \sim 610$ to 130, making Boo, the most distorted known Milky Way dwarf galaxy, potentially also the darkest. From the spectra of Boo member stars we estimate its metallicity to be [Fe/H] ~ -2.5, which would make it the most metal poor dSph known to date.

Subject headings: galaxies: individual (Boötes dwarf spheroidal) – galaxies: kinematics and dynamics – Local Group

1. Introduction

Since the early work of Aaronson (1983) on the Draco system, dwarf spheroidal (dSph) galaxies in the Local Group have been suspected to be heavily dark matter (DM) dominated. Analyses of dSph internal dynamics under the assumption of virial equilibrium suggest mass contents far exceeding those inferred from their luminosities, with central mass-to-light ratios (M/L) ranging from a few to about a hundred (in solar units). Such M/L imply that dSphs have the largest DM fraction of all galaxy types in the universe. Yet, despite the wide range of inferred M/L for dSphs, their central velocity dispersions ($\sigma_{\rm o}$) and half-light radii ($r_{\rm h}$)

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seem to be remarkably similar, $\sim 7 - 10$ km s^{-1} and $\sim$ 200 pc respectively. Using these values, typical total dSph masses of a few times 10^7 M$_\odot$ are inferred (e.g., Mateo 1998)[1]. This mass conspiracy seemingly extends to even the very low end of the galaxy luminosity scale. An early kinematical survey of the dSph in Ursa Major (UMa; Kleyna et al. 2005), the faintest and most diffuse of the known Milky Way (MW) dwarf satellites (Willman et al. 2005, hereafter W05), found $\sigma_\mathrm{o} = 9.3^{+11.7}_{-1.2}$ km s^{-1}, which, coupled with UMa's r_h of 250 pc, also results in a mass of $\sim 10^7$ M$_\odot$.

Recently, a new Galactic dSph candidate has been found in the constellation of Boötes (Belokurov et al. 2006b, hereafter B06b) during a search for halo substructure using Sloan Digital Sky Survey (SDSS; Abazajian et al. 2005) data. Along with UMa, Boötes (Boo) is one of the faintest MW satellites found, having (at a 60 kpc distance) an absolute magnitude of $M_V = -5.8$ (but maybe brighter; see §3.2). In addition, the Boo dSph exhibits the most irregular density contours of any Galactic dSph (B06b), which suggests that the satellite may be undergoing tidal disruption.

In this Letter, we present the results of a spectroscopic survey of Boo candidate stars. We have identified its kinematical signature, which allows us to estimate its systemic velocity, mass and central density, as well as its M/L. We also use the spectral data to make a rough measurement of the metallicity of Boo giant stars.

2. Spectroscopic Observations and Data Reduction

Though B06b detected Boo as an overdensity in SDSS Data Release 5 (DR5), that dataset was proprietary at the time we selected observing targets. However, Boo appears near the northern limit of the SDSS Data Release 4 (DR4, Adelman-McCarthy et al. 2006) as well. Because the core of the Boo dSph is well within the DR4 coverage area, we select Boo candidate stars in the core and southward of declination ∼14.8° (Figure 1).

Spectroscopic follow-up of Boo red giant branch (RGB) and asymptotic giant branch targets with $g < 19.0$, as shown in Figure 2, was carried out with the WIYN 3.5-m Hydra multi-fiber spectrograph on UT 2006 May 6–7. Targets are distributed throughout the ∼1-degree WIYN+Hydra field of view. The 600@10.1 grating was used with the red fiber cable to yield a wavelength coverage λ = 4500–7200 Å with a spectral resolution of 2.80 Å per

[1]Recent kinematical studies of dSphs have attempted to derive their mass content by modeling the shape of the velocity dispersion profile (e.g., Kleyna et al. 2002; Walker et al. 2006a,b), but these calculations do not take into account likely tidal effects in the outskirts of dSphs, as pointed out by Łokas, Mamon, & Prada (2005); Muñoz et al. (2005, 2006); Westfall et al. (2006); Sohn et al. (2006).

resolution element. To achieve adequate S/N for velocity determination, we observed one Hydra configuration containing 72 Boo candidate stars for 4×30 min. We also observed 9 radial velocity (RV) standards covering spectral types F through M, each through multiple fibers, yielding a total of 64 RV cross-correlation template spectra.

Preliminary processing used the *IRAF* CCDRED package, with spectral reduction following the standard DOHYDRA routine. RVs were derived using the *IRAF* FXCOR task, with each spectrum cross-correlated against all RV standard spectra. The regions around the Hα, Mg triplet, and Hβ lines were used for cross-correlation. In the end, we measured reliable RVs for 58 of the 72 observed Boo candidates. RV standards (observed multiple times) showed deviations from the published IAU values for V_r of less than 1 km s^{-1} on average.

RV uncertainties were determined using the Vogt et al. (1995) method, based on analysis of repeatedly observed standard-star spectra. This technique takes advantage of the fact that the Tonry-Davis Ratio (TDR, Tonry & Davis 1979) scales with S/N, so that individual RV uncertainties may be found via: $Error(V_r) = \alpha/(1 + TDR)$, where α is determined from the standards. For our set of 64 standards, we measure $\alpha = 107$, which yields an average velocity uncertainty of ~ 4.0 km s^{-1} (TDR > 25, with typical S/N of 15-20).

3. Spectroscopic Results

3.1. Bootes Membership

With our RV data alone, the signal of Boo stars is not clear. To improve the contrast of Boo stars with respect to MW contaminants, we make use of the gravity sensitive MgH absorption feature near 5150 Å to remove foreground Galactic dwarfs, as we have done photometrically in our previous dSph studies (e.g., Majewski et al. 2005; Muñoz et al. 2005, 2006; Westfall et al. 2006). Because the MgH absorption is very strong in all but the most metal-poor ([Fe/H] $\lesssim$ -2) K–dwarf stars, visual inspection alone is sufficient to "clean" our spectroscopic sample of the majority of foreground dwarfs by simply identifying those with strong MgH features, like the one shown in Fig. 4 (see also Fig. 1 in Majewski et al. 2000 for an illustration).

To further clean this sample, we make use of instrumental Lick spectroscopic indices (Worthey et al. 1994). A proper determination of stellar $T_{\rm eff}$, log g and [Fe/H] values based on Lick indices is beyond the purpose here. Instead, we identify stars with similar metal line strengths using the quantitative indices of the Lick system. Figure 3a shows the Mg$_1$ + Mg$_2$ versus Mg b trend for all stars visually classified as likely giants with RV uncertainties less

than 7.5 km s^{-1}. Figure 3b shows their RV distribution as a function of radial distance from the nominal center of Boo. We have marked those having relatively low and high Mg indices with circles and squares respectively. We also mark with asterisks a group of stars clumped in V_r ($\sim$ 50 km s^{-1} in Fig. 3b) and Mg strength. These stars have velocities compatible with those expected for debris from the leading arm of the Sagittarius (Sgr) dSph (Law et al. 2004); because Boo lies in the background of the Sgr leading arm (see Fig. 1 in Belokurov et al. 2006a), giant stars with these RVs are not unexpected in our sample. Figure 3b shows that within the r_h of Boo the distribution of stars shows a distinct grouping of giant stars with low Mg indices and $V_r \sim 100$ km s^{-1}. Such a velocity grouping is unexpected for a random halo population at this Galactic position, and is clearly distinct from the distribution of stars beyond r_h, which is centered at 0 km s^{-1} (the nominal mean velocity for any MW stellar population at this Galactic longitude). A two-sample Kolmogorov-Smirnov test shows that the populations inside and outside $13'$ are drawn from different RV distributions with a probability greater than 99.99%. Thus, we identify this group of RV-clumped stars within $13'$ with the Boo dSph.

This "cleaner" RV distribution inside r_h helps us define a membership criterion to identify Boo stars. We first draw attention to the broadening of the RV distribution beyond $\sim 10'$. This behavior might be expected if Boo is undergoing tidal stripping, as its distorted morphology suggests. Models of tidally disrupting satellites predict a rising velocity dispersion at large radii (e.g., Kroupa 1997), a trend that is also observed in a number of other Galactic dSphs: Ursa Minor (UMi, Muñoz et al. 2005), Sculptor (Westfall et al. 2006), Carina (Muñoz et al. 2006), Fornax (Walker et al. 2006a), Sextans (Walker et al. 2006b) and Leo I (Sohn et al. 2006). Because of the broadening of the RV distribution, we conservatively use the innermost seven stars to define a 3σ (see §3.2) RV criterion for membership of $75 < V_r < 116$ km s^{-1}. Twelve stars lie within this velocity range, all with low Mg line strengths, the most widely separated (within our survey) at $27'$ to the south of the Boo center.

Two likely giants at higher velocity than our 3σ RV limit are seen in Figure 3b. They lie right in the narrow RGB of Boo (see Fig. 2 where they are marked with open circles) and the strength of their Mg features makes them consistent with being Boo members; these stars suggest a possibly dramatic increase of the Boo velocity dispersion with radius.

3.2. Velocity Dispersion, Mass and M/L

Using the innermost seven stars to define the properties of the Boo core RV distribution gives a systemic velocity of $V_r = 95.6 \pm 3.4$ km s^{-1} and a velocity dispersion of σ_o =

6.6 ± 2.3 km s^{-1}, calculated using the Maximum Likelihood Method (Pryor & Meylan 1993; Hargreaves et al. 1994; Kleyna et al. 2002). This V_r translates into a $V_{GSR} = 102.9 \pm 2.8$ km s^{-1}, implying that Boo is likely not in a circular orbit, but in a rather radial one. Including all twelve potential 3σ members in the calculation yields $V_r = 98.4 \pm 2.9$ km s^{-1} and $\sigma_{\rm o} = 9.0 \pm 2.2$ km s^{-1}; the latter corroborating the apparent increase of the velocity dispersion with radius. If we include the two likely high velocity members that lie above the 3σ RV limit (§3.1), we obtain $\sigma_{\rm o} = 14.6 \pm 3.0$ km s^{-1}.

As is customary for this type of study, one can use the observed $\sigma_{\rm o}$ to estimate the mass content in the Boo dSph under the assumption that it is in dynamical equilibrium. While this assumption has been a matter of some debate, it has been shown (e.g., Piatek & Pryor 1995; Oh, Lin, & Aarseth 1995; Kroupa 1997; Muñoz et al., in prep.) that unless the satellite is completely destroyed or near complete destruction, the value of $\sigma_{\rm o}$ indeed reflects the instantaneous mass content. From Illingworth (1976), the total mass of the dSph system can be approximated by: $M_{\rm tot} = 167\beta R_{c,g} V_s^2$, where β is a correction parameter dependent on the concentration value, $R_{c,g}$ is the geometric-mean King core radius in pc, and $V_{\rm s}$ is a parameter related to $\sigma_{\rm o}$. Mateo (1998) approximates $\beta = 8.0$ and $V_s \sim \sigma_{\rm o}$ for pressure-supported systems that follow low concentration King models, as dSphs do. We can further approximate $R_{c,g}$ to $r_{\rm h}$ derived by B06b ($13'$, corresponding to 225 pc at a distance of 60 kpc). With $\sigma_{\rm o} = 6.6 \pm 2.3$ km s^{-1} we obtain $M_{\rm tot} = 1.1^{+1.3}_{-0.5} \times 10^7$ M$_\odot$. We can also estimate the central mass density in Boo as $\rho_{\rm o} \approx 166\sigma_{\rm o}^2\ R_{c,g}^2$ (Mateo 1998); this yields $\rho_{\rm o} = 0.14 M_\odot$ pc^{-3}.

These results are remarkably similar to the values obtained for the majority of the Galactic dSphs. Mateo (1998) points out that Local Group dSph systems seem to be embedded in DM halos of $M_{\rm tot} \approx 10^7$ M$_\odot$ regardless of the contribution of their luminous component. He further finds the following empirical relation between the M/L and the total luminosity of a dSph: $M/L = 2.5 + [10^7/(L/L_\odot)]$. Adopting an absolute magnitude for Boo of $M_{\rm V} = -5.8$ (from B06b) yields a total luminosity of $L_{\rm V} = 1.8 \times 10^4$ L$_\odot$, which, in turn, gives $M/L_{\rm V} = 610$ (M/L)$_\odot$. We note that this luminosity would make Boo even fainter than UMa if we adopt for the latter the absolute magnitude estimate of $M_{\rm V} = -6.75$ from W05. A visual comparison of the CMDs of Boo and UMa reveals that the Boo RGB contains at least a factor of two more stars than that of UMa (see also Siegel 2006). Since they have comparable half-light radii, this implies that Boo must be at least twice as bright as UMa. Were we to adopt the W05 estimate for the UMa $M_{\rm V}$, this yields a total luminosity for Boo of $L_{\rm V} \sim 8.6 \times 10^4$ L$_\odot$, making $M/L_{\rm V} = 130$. With either of these values, however, Boo lies squarely on the Mateo (1998) relation.

3.3. Metallicity

The Mg I triplet+MgH absorption features near 5150 Å can be exploited to estimate the Boo [Fe/H]. We have already shown (Fig. 3) that Boo stars exhibit by far the weakest Mg features of all likely giant stars in our sample. We have used the CTIO 4-m telescope + the Hydra multifiber spectrograph, with a comparable instrument setup (yielding similar spectral resolution) to that used for the Boo observations, for RV measurements of red giant candidates in the globular clusters (GCs) NGC 288 and NGC 5634 (Moskowitz et al., in prep.). These clusters have [Fe/H] of −1.24 and −1.88 respectively (Harris 1996) and we use them as metallicity calibrators, selecting for this purpose giant stars that are confirmed RV cluster members. In order to minimize the effect of surface gravity and temperature in the measurements of equivalent width (EW) of the Mg features, we pick and combine the spectra of stars that lie in the upper part of their respective red giant branches, which provides bright members with fairly similar colors. Figure 4 shows the combined spectra obtained for the two clusters and for Boo. We then add the EWs for the three Mg lines to compensate for the weakness of the Mg features, and assume a linear function between this sum and [Fe/H][2]. Using this derived relationship and assuming a similar [Mg/Fe] ratio between the GC and Boo stars[3], we translate the EWs measured for Boo into an extrapolated [Fe/H] of −2.5. The uncertainties in the EW measurements translate into uncertainties in [Fe/H] of about 0.2 dex. This does not include, of course, the error introduced by assuming a linear relationship between EWs and [Fe/H] in the first place, nor the uncertainties due to surface gravity, temperature effects, or possible variations in α-element abundances between the GCs and Boo.

These calculations, although only intended to provide a very rough estimation of the metallicity of Boo, are consistent with the [Fe/H] = −2.6 derived by Siegel (2006) using RR Lyrae variables, and with the fact that the Boo RGB seems to be slightly bluer than that of M92 ([Fe/H] = −2.3; see Fig. 2 of B06b). Boo is potentially the most metal poor of the Galactic dSphs known to date.

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[2]Figure 9 from Buzzoni, Gariboldi, & Mantegazza (1992) suggests that a linear relationship between Mg_2 and [Fe/H] is not unreasonable for [Fe/H] < -1.3.

[3]Shetrone, Cote, & Sargent (2001) and Shetrone et al. (2003) showed that metal poor stars in Sculptor, Leo I and UMi ([Fe/H] < -2.0) have comparable [α/Fe] to Galactic GC stars.

4. Discussion

We spectroscopically survey the Boo dSph and derive both its systemic velocity (95.6 ± 3.4 km s^{-1}) and central velocity dispersion (6.6 ± 2.3 km s^{-1}), which yields a mass of $M_{\rm tot} = 1.1^{+1.3}_{-0.5} \times 10^7$ M$_\odot$. This mass is similar to that of the other dSph galaxies and puts Boo squarely on the "same mass-just different luminosities" trend identified by Mateo (1998), despite the fact that Boo is one of the faintest known Galactic satellites.

The dynamical mass derived for Boo, taken at face value, implies that this is possibly also the darkest dSph known to date. If other systems of similar luminosity have the same mass, the current pace of discovery of these systems (three in the past year; W05; Zucker et al. 2006; B06b) — and in only the approximately 20% of the sky covered by the SDSS DR5 — will help alleviate the current order of magnitude or two deficit of known Galactic satellites compared to that predicted by ΛCDM simulations, albeit only for one part of the mass spectrum exhibiting the apparent "missing satellites" shortfall (e.g., Klypin et al. 1999). While Boo seems to be the most DM dominated dwarf, it is, at the same time, the Galactic satellite with the most distorted known morphology (B06b) and possibly most dramatic increase in velocity dispersion with radius. This implies that Boo may be among the most disrupted Galactic dwarfs, to the extent that it even lacks a proper core (B06b). In fact a puzzling correlation is now emerging between the DM fraction of a dSph and its morphology, wherein the faintest and most distorted systems (the UMi, UMa and Boo dSphs) seem also to present the largest central M/L's. If the distorted contours are a response to the influence of Galactic tides, and if all dSphs indeed have a similar current total mass and density, then why is it that tides seem to affect preferentially the least luminous systems? Perhaps these faintest systems represent the Kroupa (1997) regime in which disruption has proceeded to the point where the central velocity dispersions are inflated by tides, artificially increasing the derived M/L. But even if so, then it is curious that the current $\sigma_{\rm o}$ for Boo would be inflated to just such a value that the derived (but artificial) dynamical mass still participates in the "same mass" conspiracy of dSph galaxies.

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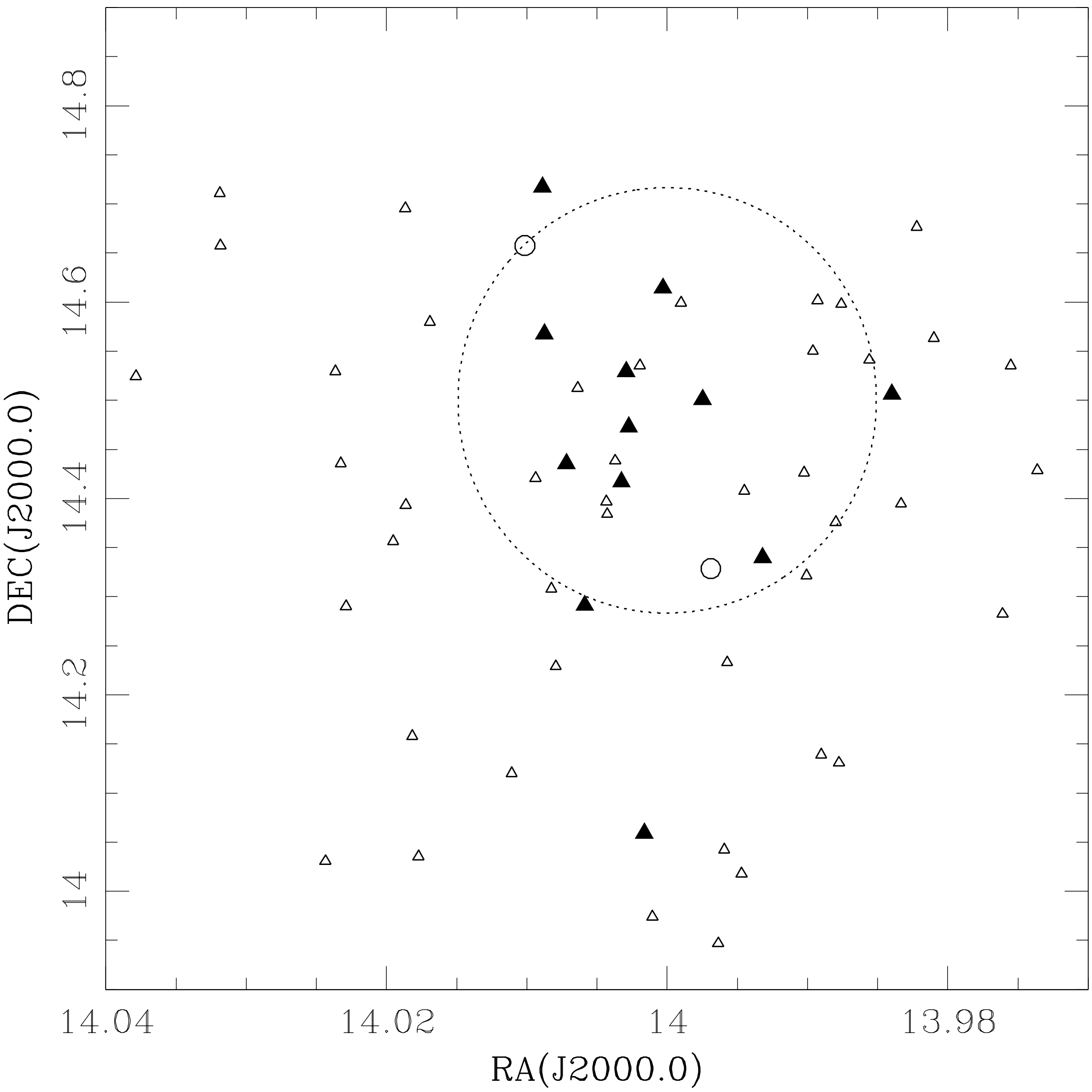

Fig. 1.— Spatial distribution of all 58 stars with measured RVs. Filled triangles correspond to the final Boo sample (from Fig. 3 analysis), while open triangles mark stars not considered members. Two open circles represent the higher-velocity stars discussed in the text as possible members based on the similarity of their Mg indices to those of other Boo stars. The Boo $r_{\rm h}$ determined by B06b is delineated by the dotted circle.

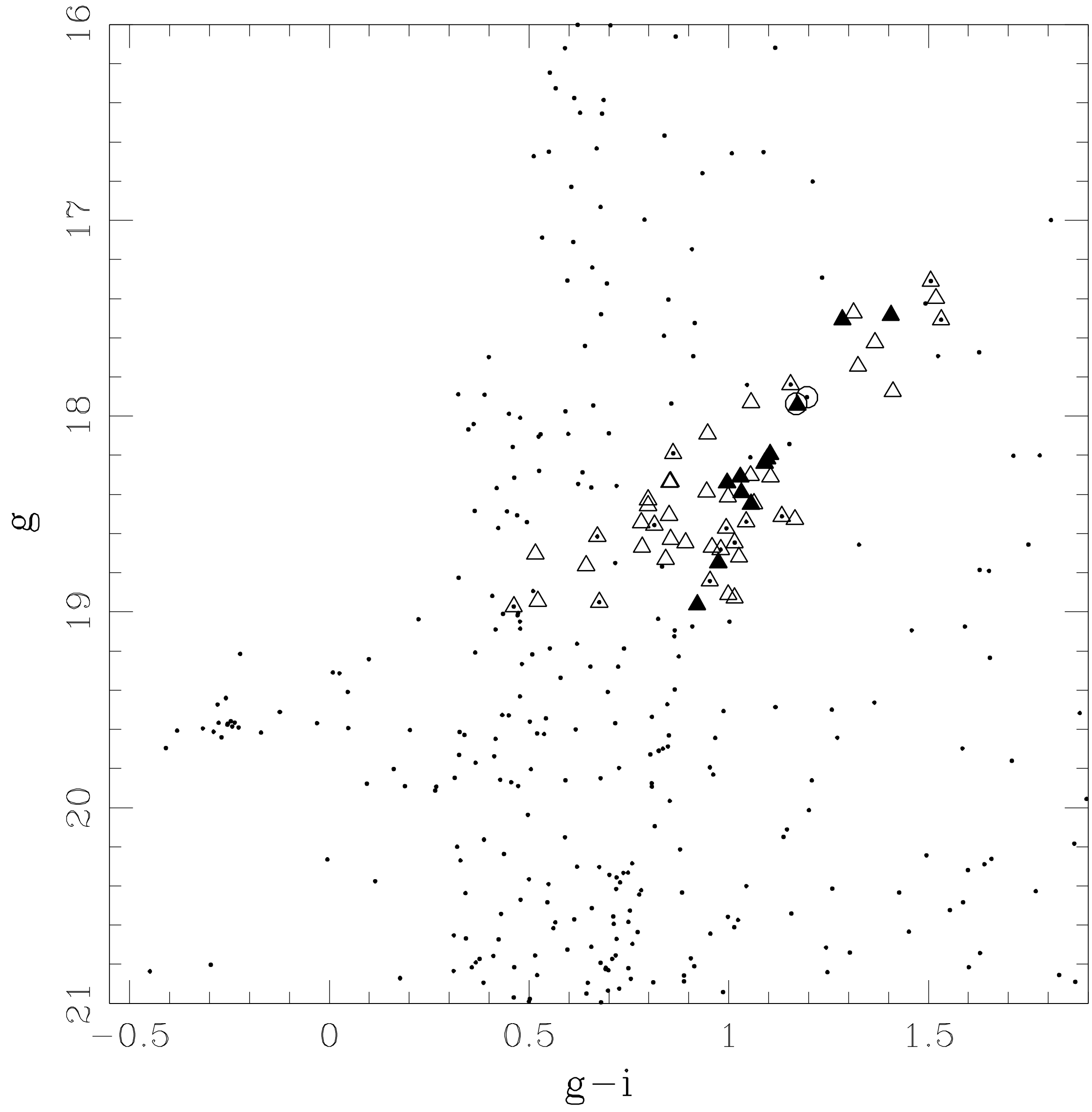

Fig. 2.— CMD of the Boo region showing the clear Boo RGB and horizontal branch. The dots represent stars within the $r_{\rm h}$ of Boo (dotted circle in Fig. 1) in order to highlight Boo's features, while the other symbols show *all* 58 stars as in Fig. 1.

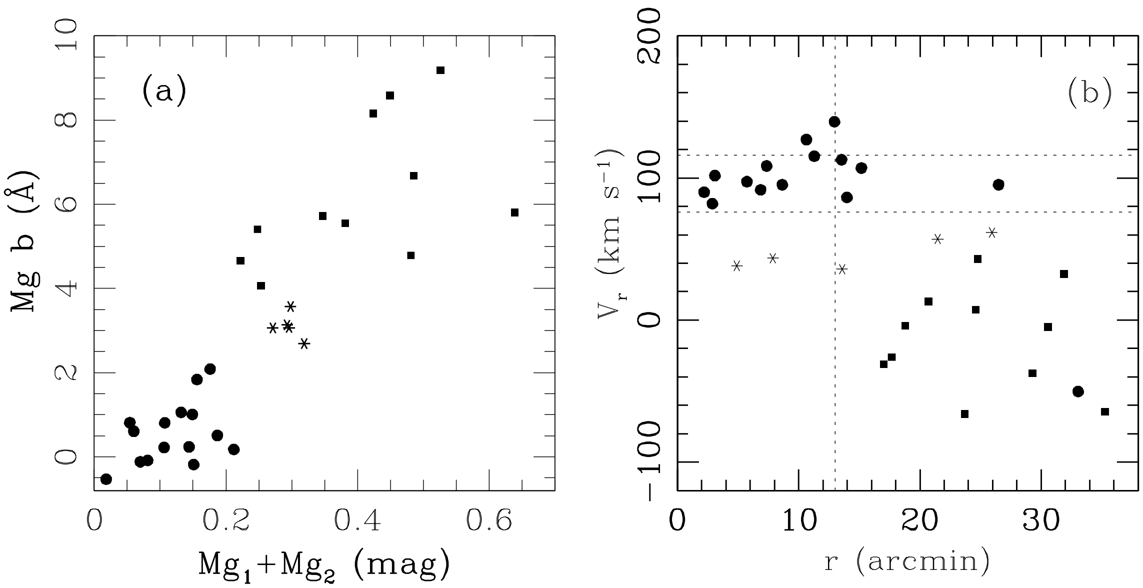

Fig. 3.— (a) $\mathrm{Mg_1{+}Mg_2}$ versus Mg b instrumental Lick indices for all stars with velocity uncertainties < 7.5 km s^{-1} visually classified as likely giants. Circles mark stars most likely to be metal poor, while squares show stars more likely to be metal rich. We mark with asterisks a clump of stars with similar indices and RVs, possibly from the Sgr dSph. (b) RVs of all stars in (a) as a function of radial distance from the center of the Boo dSph. Symbols as in panel (a). The dotted vertical line marks the Boo $r_{\rm h}$, while the dotted horizontal lines delimit a 3σ RV spread. The two higher-velocity stars discussed in §3.1–3.2 (open circles in Fig. 1) lie just above the upper 3σ limit.

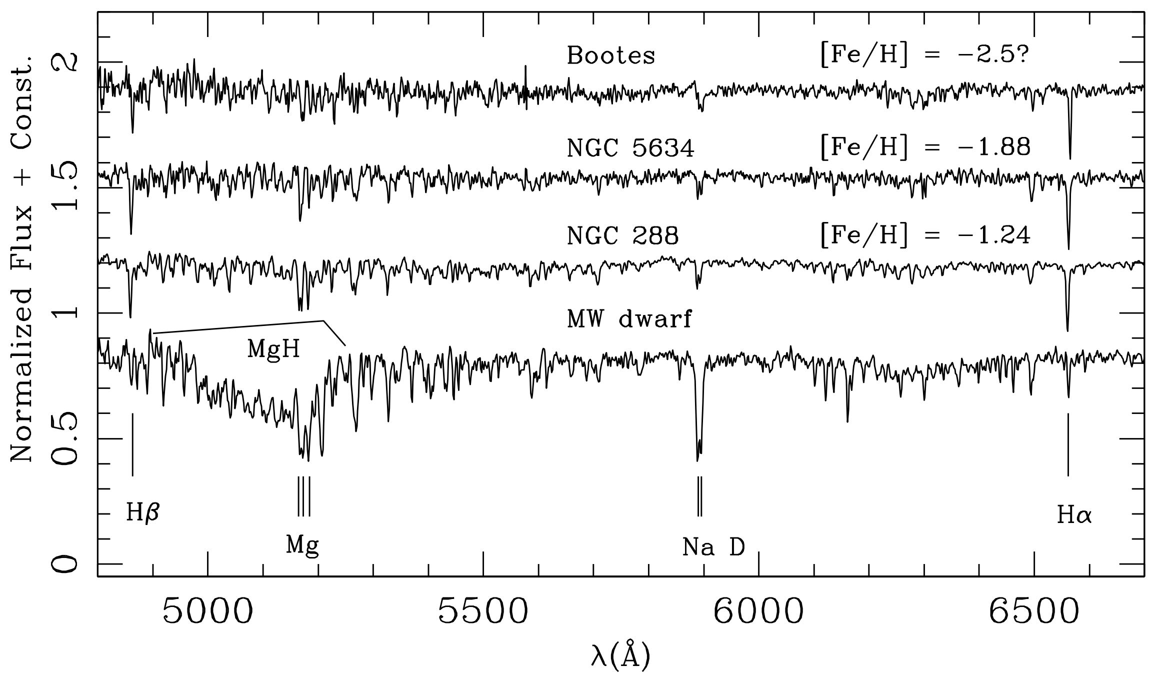

Fig. 4.— Sample of the spectra used to estimate the metallicity of Boo. From top to bottom: Combined spectrum of the three brightest Boo giant stars, combined spectrum for NGC 5634 giants and combined spectrum for NGC 288 giant stars. The comparison spectrum of a dwarf star demonstrates the broad MgH absorption feature between ∼4900-5250 Å, which is an obvious signature of late G or K dwarf stars.